Potter, K. D. (2016). 'But How Can We Make Something Useful Out of Black String?' The Development of Carbon Fibre Composites Manufacturing (1965–2015). In P. W. R. Beaumont, C. Soutis, & A. Hodzic (Eds.), *The Structural Integrity of Carbon Fibre Composites: Fifty Years of Progress and Achievement of the Science, Development, and Applications* (pp. 29-57). Springer International Publishing AG. https://doi.org/10.1007/978-3-319-46120-5_2

"But how can we make something useful out of black string?"

The development of carbon fibre composites manufacturing 1965-2015

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Abstract.

This chapter looks at how the manufacturing community responded to the invention of carbon fibres, the first practical, high-modulus, reinforcement to be available as continuous fibres; largely through the lens of the author's personal experience. Whilst it seems axiomatic to us today that we use continuous fibres, most of the composites applications in 1965 used short fibres, for example chopped glass, asbestos, whiskers or linen fibres. To a large extent the narrative of carbon fibre composites manufacturing is the story of how to manipulate continuous fibres into complex geometries; and how to do that cost-effectively without introducing strength reducing defects. Until very recently, when the manufacturing and structural integrity communities have started to interact much more, there has tended to be an almost complete disconnect between the materials, design and manufacturing worlds. This has been the case as much in industry as it has in academia and seems to have been the norm since the very beginnings of the application of carbon fibre composites. The difficulties inherent in manufacturing geometrically complex parts were identified very early in the history of carbon fibre composites. However, it has proven to be very challenging to go beyond identifying problem issues to actually solving them, and that process is by no means complete. There are signs that the composites community may finally be on the right track, with some recent successes pointing towards research directions where design and manufacturing approaches can be unified to deliver reliable and cost-effective parts - only 50 years after the process started.

Introduction

The author first encountered carbon fibre reinforced composites in 1971 in his Materials Science BSc course, then in only its second year at Imperial College, London. Carbon fibre was more or less mentioned in passing in a very few lectures, then passed over quickly so that we could get back to studying metals. On graduating in 1974 the author joined the group working on various types of composites at the Explosives Research and Development Establishment (ERDE) at Waltham Abbey in the UK. From the beginning the author's work was primarily focused on composites manufacturing, and has continued to be so until today in both industrial and academic settings. Since then, all the author's career has been in composites, in the development of manufacturing processes, in product design and development, in shop floor manufacturing of composite parts and latterly in academic research and development. Roughly half the author's working life has been in "commercial" activity and half in academic. That's the end of the CV. From here on the approach will be a mixture of the historical and the thematic aiming to give a flavour of the areas of development, and where significant improvements still need to be made. This chapter will principally cover the three areas of composites manufacturing that have dominated the author's career; understanding prepreg lay-up, and reinforcement deformation issues; the development of Resin Transfer Moulding; and lastly understanding defects and variability in composites manufacturing. The chapter will be closed off with a brief discussion of the state of the art in modelling and predictive tools to support composites manufacture.

1 Understanding Prepreg Lay-up.

1.1 Background and early history

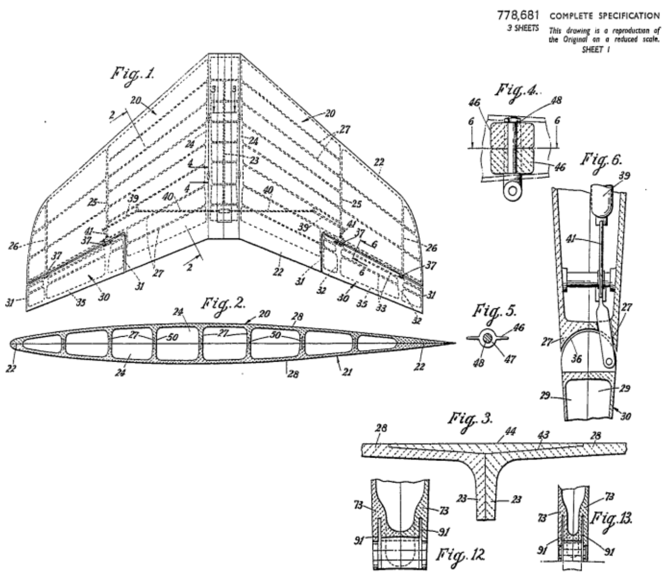
The relationship between materials scientists, designers and manufacturing people has been a somewhat fraught one since the very start of the carbon fibre composites industry. This can be explored by quoting one of the fathers of carbon fibre composites, Leslie Phillips, from a paper on composites manufacture in the first volume of "Composites" from 1969 [1]. The following is the introduction to the paper. "Having decided that CFRP is here to stay, the reader wonders whether fabrication is restricted to a small number of firms or whether anyone can join in. The answer is that the technique can be learned and applied by competent engineers in a matter of weeks rather than months. If there is previous experience with other fibre-reinforced materials such as glass or asbestos the period can be even shorter". With all possible respect due to one of the founding fathers of advanced composites, he was spectacularly wrong. More than 45 years down the road it would be fair to say that the composites community is getting better at manufacture, but in some respects it is only now beginning to deal properly with the complexity of manufacturing arbitrary geometries, reliably, reproducibly and to a high quality standard - and doing that affordably is still a very real challenge.

From the perspective of carbon fibre / advanced composites it is easy to overlook that there was a well-developed composites manufacturing industry before the invention of carbon fibre, and that in tonnage terms glass rather than carbon fibre is still dominant. In other papers from that first volume of "Composites" the available composites manufacturing processes are described [2, 3]. In total 14 processes are identified, covering everything from contact moulding to filament winding to autoclave moulding and Resin Injection (as RTM was then known). In essence all of the current composites moulding processes were available in 1969, even if they were in many cases only weakly developed; and in truth even more weakly understood in any scientific sense. The 1950s were actually the decade in which most of our modern composites manufacturing processes were initially developed. Fig 1 shows a couple of images taken from patents applied for in 1952 and 1955.

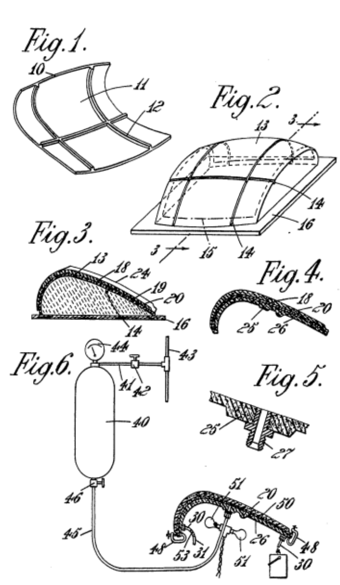
In addition to the processes themselves the design philosophy embedded in these patents is still very relevant today. The sentences below are a direct quotation from the 1952 patent and perfectly encapsulate the challenge that the industry still faces today..

"The invention enables a single moulding to be used for the upper half of one wing and the lower half of the other wing. In this manner both wings are made up from only two mouldings. The small number of mouldings enables the wings to be made cheaply and rapidly by mass production methods, the subsequent assembly operation enabling the minimum work, time and labour"

Automated tape laying and fibre placement are the only major processes where development started after the 1950s, and they are really fibre collation processes rather than moulding processes; even in this case the earliest known patent dates to 1967 (US3574040 filed by General Dynamics).



Application date 1952. Aircraft wing structure made by compression / injection moulding of asbestos reinforced phenolic resin



Application date 1955. Resin Transfer Moulding of complex geometries

Fig 1. Patents drawings relating to composites manufacture from the 1950s.

The 1969 paper [2] shows many articles of complex geometry being made from glass reinforced composites, and these shared one common factor, the glass has been chopped into fairly short lengths and randomly arranged into a formable sheet, or sprayed directly onto a tool surface or onto a preform tool. To a first approximation most of those applications of glass fibre composites were semi-structural and in weight-insensitive structures, primarily taking advantage of the material's ability to generate the smooth, thin shells of complex, doubly curved geometry which are very expensive to fabricate in metal. In this respect glass fibre composites were perhaps closest to filling the same design niche as papier mâché did in Victorian England, and papyrus cartonnage did in Pharaonic Egypt. A very strong case can be made for cartonnage mummy cases as the first "modern" composite structures.

This was never the target for carbon fibre composites, which were always intended for use in the structural applications (primarily in aircraft) for which their high moduli were essential. [4] gives a history of the early years of aircraft composites and [5] gives a more recent overview. To maintain the high moduli (and avoid a waste of extremely costly material) the assumed design and manufacturing philosophy was to use the new material in continuous form at a high volume fraction of fibres. The slight problem in the very early days was that the tows of fibre were longish, but not continuous.

The early, 1m long, Morganite Carbon fibre made in the mid-1960s came in packages, carefully wrapped in brown paper and, when unwrapped, the individual tows could be very carefully extracted. This dissonance between a demand to maintain good alignment and a high volume fraction, and only having relatively short lengths of fibre, led to the development of the "Leaky mould" technique. Tows of carbon fibre were saturated in resin and very carefully placed by hand into a mould cavity until the right charge weight has been achieved. The second part of the mould was then put in place and a combination of pressure and temperature was used to consolidate the lay-up, eliminate excess resin, limit voidage and cure the resin. This is not a process where it will be easy to achieve a consistent result. The leaky mould technique has another, probably more critical limitation, it could only really make unidirectional (UD) specimens for test. This may have contributed to some of the early overselling of carbon fibre laminate properties, as only UD properties were readily available. An alternative approach based on impregnation of tows laid side by side with a solution of epoxy resin in acetone gave an intermediate material form (unidirectional [UD] prepreg) that was more easily handled, and with which it was possible to make multi-directional laminates. More importantly, with UD prepreg manufacture could move out of the lab and on to the factory floor to make objects with a bit of shape to them - but not very much because UD prepreg is still far from easy to do much with in terms of very complex geometry.

The very first prepregs were made from the original short lengths of fibre, but as continuous fibre became more widely available turning it into UD prepreg was the obvious thing to do. As noted earlier these continuous fibre UD prepregs were rather tricky to work with, they tended to tear and wrinkle easily when being sheared and stretched transversely to form onto a surface of double curvature, and the handling properties were very sensitive to temperature. Far from being easy to apply they needed very skilled staff to make anything other than flat sheet, and this is as true today as it was in 1970. The early resin matrices were also very troublesome to work with, falling to very low viscosities in the heat up to cure and requiring real care to ensure that the resin flow was not excessive in cure, leading to voidy laminates [6]. The acceptable process window in many cases was close to zero. The obvious solutions to the problems with lay-up on complex shapes could be seen in the experience with earlier classes of fibre. If the fibres are continuous like glass, then chop and randomly disperse them or weave them, if the fibres are short such as asbestos or whiskers then form them into felts with a level of fibre alignment to maintain good properties. It took a few years to work out how to weave carbon fibres without damage, and the techniques developed earlier at ERDE to sort and align whiskers and asbestos fibres could be applied to the production of high performance aligned short carbon fibre felts.

In 1974 woven carbon fibre textiles were just becoming available, the team at ERDE had demonstrated that short, chopped carbon fibres could be aligned extremely well [7], and soon after that the first of the second generation prepreg systems with some thermoplastic additives that stopped viscosity falling too far were becoming available. These second generation systems were a revelation, it was no longer necessary to be extremely careful in designing the bleed pack and exact point of autoclave pressure application to get a decent quality laminate. They made many intractable moulding problems disappear overnight.

1.2. The early development of an understanding of reinforcement deformation.

Most of the author's early work was in thinking about how to make things. A fairly typical example was a helicopter tail rotor gearbox, essentially a flanged cone with local deviations from a simple volume of revolution. It was very difficult to form the multiple curvatures required from continuous UD prepreg, but much easier to build if the reinforcement has a degree of manufacturing ductility, for example achieved in a highly aligned but discontinuous fibre prepreg [8]. One thing that was becoming increasingly obvious was that how the reinforcement formed to the tool was absolutely critical and would largely control the cost-effectiveness of composite applications. This was the initial interest in understanding drape and reinforcement deformation properties; as things developed it became clear that it was also critical from a performance viewpoint - in terms of being able to avoid wrinkled plies. This interest led to the start of a study in how to understand, model and control the forming of composite reinforcements, both woven and unidirectional, and later non-crimp fabrics. The study probably started in the mid1970s, and was reported on in a couple of papers in 1979 [8,9]. The most recent paper in this area from the Bristol University team was published in 2015 [10] and the field is still very much "live". It has taken more than 35 years to reach the current level of understanding, but it now seems possible to close out this area of study in the not too distant future.

From the beginning there have been two strands to the study of reinforcement deformation. The first relates to trying to understand the deformation and forming properties of composites reinforcement from both scientific and practical viewpoints. The second relates to how to use that developing understanding to deliver manufacturing solutions and understand issues of Design for Manufacture, although on the academic side the first strand has been heavily dominant.

Automated solutions to composites manufacture are becoming much more common, but in the first decade of carbon fibre composites the only realistic option was manual lay-up of unidirectional prepreg. Even today for the fairly small and complex parts that make up the bulk of aircraft secondary structures, and essentially everything in Motorsport, manual lay-up still dominates, but generally with woven rather than UD reinforcements, see fig 2.

Fig2. Typical complex very low volume automotive component (door liner from a supercar).

The recognition that the costs and difficulty of manual lay-up were a major obstacle to the development of composites was made very early on by several groups, with the first US patents for what are recognisably Automated Tape Laying (ATL) or Automated Fibre Placement (AFP) machines dating from the early 1970s [11], and a UK developed ATL was reported at a conference in 1980 [12]. Interestingly, an essentially identical machine was demonstrated at a major trade show in 2015 [JEC Paris].

The early Conference and Journal papers on the drape of reinforcements seemed to disappear without trace at the time, but slowly, over time, the number of papers started to grow significantly, with pretty much an exponential growth from 1985-2015. As the study of reinforcement deformations became more mainstream, and the number of papers greatly expanded and became focused almost entirely on woven cloths, the study tended to narrow down to how to model the drape of woven cloths over arbitrary surfaces. This is clearly very important, but it must be stressed that it doesn't actually directly answer the questions around how to support, or improve the manual lay-up processes, much less the question of how to improve designs or automate manufacture. It has taken the whole community, the author included, far too long to long to understand this. With regard to automation it is really rather surprising how little some of the early work attempting robotic lay-up took account of the practicalities of how the reinforcement was actually applied to the tool by the skilled laminators [13]. Equally, designers of composite parts have not generally taken much account of the difficulties of manufacturing the parts that they design. Realistically, when manufacturing engineers have been unable to tell designers what a good, manufacturable, design that makes best use of laminator skills and reinforcement formability actually looks like, to minimize costs or maximize quality, it is unsurprising that the designers often take little account of manufacturability. Recent work has been investigating how the experience and expertise of laminators can be brought into the design process by facilitating structured conversations between designers and laminators. It has been very instructive how positive the interactions have been, so it does seem to be a pity that it has taken so long to engage two of the main sets of players in the composites community.

1.3. Drape modelling

Before moving on to how to understand what is meant by manufacturability it is worth recapping on the drape of woven cloths. The mechanism by which woven cloth could be formed to surfaces was certainly recognised by the textile community by 1956 (14), and considerably earlier in dressmaking, although the 1956 paper seems to be the first mathematical treatment. Cloths are assumed to deform by a process of trellis shear, as if the warp and weft formed a pin-jointed net, and experimental testing very largely bears this out as a reasonable assumption. However, it's easy to identify the basic process and much harder to do something useful with it. The 1956 Mack and Taylor paper that is generally credited with starting this study in many ways simplified the surface fitting problem by setting it up in such a way that the warp/weft angle remains constant at any latitude on a sphere being fitted with a strip of bias cut woven cloth. This is very much a special case and doesn't really correspond to the generality of composites manufacture. A more generalised case would be to take a sheet of woven cloth, drop it onto a spherical or more complex surface and smooth it down onto the surface. In this case the warp/weft angle at any latitude changes dramatically around the circumference of the spherical surface. This drape over a hemisphere problem was to a very large extent the story of the next 20 years of drape modelling. For example, the 1979 paper [9] featured outputs from what would have been a very early computer model of cloth drape over a hemisphere, if not the first. This model lacked any sort of graphical interface or output so was of limited utility in a design environment. There have been quite a number of papers that looked at cloth drape over geometries other than hemispheres [e.g. 15] but the bulk of the early work on drape did tend to look at volumes of revolution.

It must be pointed out that skilled laminators don't actually lay up on a typical tool by placing a sheet of prepregged woven cloth at the highest, or lowest, point on the tool and working the contact area out in a spiral from that first point of contact. This is implicitly what all the early cloth drape models (and many more modern commercial offerings) are assuming, and it makes no sense on components of common practical geometries, where any sensible person would start from some datum line to ensure that the fibre directions are as designed, at least at the start of the lay-up process. It would simply be impossible to get the initial alignment correct for complex geometries, let alone to have any real control over the process by working in the real world in the way that the simple early models work.

All the early drape models were purely kinematic, they assumed completely free pin jointed net behaviour without any shear or bending stiffness. A detailed inspection of model predictions compared to experimental drape results showed some minor discrepancies, which spurred on further more detailed modelling. However, even the earliest kinematic models probably gave acceptable fidelity in terms of fibre direction, within a very few degrees of experimental data, so it is not entirely clear with 20:20 hindsight why such a lot of effort was expended on drape modelling. The industrial norm for accuracy of achieved fibre direction compared to drawing nominal is generally +/- 2 or +/-3 degrees; and it is by no means uncommon to have a single direction control rosette specified even on a complex geometry part - so even knowing what nominal direction is at any point on the component surface is non-trivial. Even the crudest models can achieve the +/- 2 or +/-3 degrees level of fidelity for drape over a hemisphere, so the effort certainly wasn't expended due to industrial demands for more accuracy. The number of papers published between 1976 and 2015 is presented in Fig 3. (Source Google Scholar, search string: papers including all the words "woven fabric drape modelling")

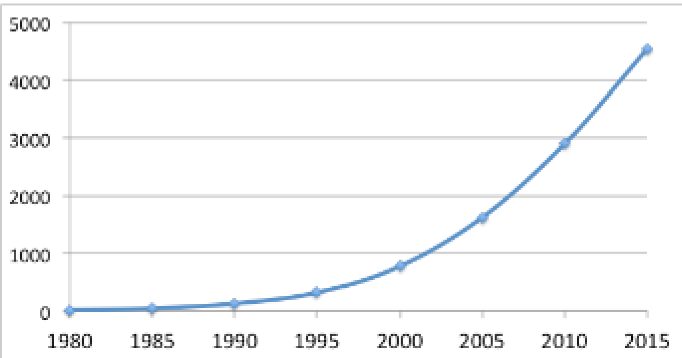


Fig 3. Drape related paper numbers 1980-2015.

This amounts to more than 4000 papers, and even allowing for capturing a lot of papers of very limited relevance does demonstrate the almost explosive growth in this area of study. Whilst the simple kinematic models compute very quickly they cannot deliver in areas such as predicting loads, the forming of stacks of plies and the generation of some sorts of forming defects such as wrinkles. To meet these requirements, simulations based on mechanics solved by FEA were developed [16,17,18]. In principle these offer much improved fidelity, but at the cost of significantly longer computation times and a significant level of materials characterisation is needed. These models essentially respond to the modelling and simulation requirements for press-forming or stamping of reinforcements rather than for manual lay-up, where they really add little or nothing to the kinematic models.

One more recently developed approach to drape modelling came about through working closely with a company that needed to understand where some of their fibre wrinkling defects were coming from. Even a brief examination of the production line showed that a drape model was needed that could replicate what the operators were actually doing, rather than what could easily be modelled. In response a new approach to drape modelling was developed - the Virtual Fabric Placement (VFP) model (19). A user of this model could essentially carry out any lay-up task in the virtual world that could be achieved in the real world; including folding, darting and local or global pre-shearing of the virtual reinforcement. Very complex geometry surfaces could be draped in VFP that would simply crash a conventional drape model, and could be demonstrated to work in the real world. Fig 4.

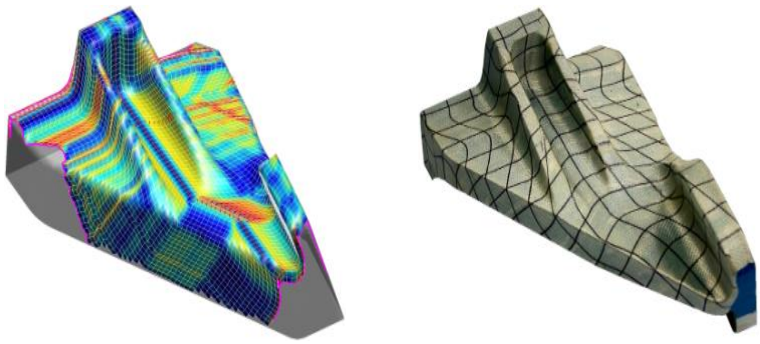


Fig 4. VFP model output (left): Woven glass cloth laid up on tool (right)

The intention was to use VFP in a design environment to debug and troubleshoot the design virtually by simulating how each ply could be applied to the tool surface without defects, and then generate totally unambiguous Manufacturing Instruction Sheets to improve quality and reproducibility. However, further work showed that although the VFP programme could be used to instruct an operator to proceed in a specific fashion, it could not, of itself, identify whether that fashion would lead necessarily to a cost-effective solution, or identify what the best approach to lay-up would be, although it could be used to avoid the generation of significant defects.

1.4. Understanding manufacturability

In recent years there has been much more serious work carried out on automated manufacture along a few tracks in both academia and in industry.

Automated Fibre Placement machines were developed to do several things, essentially to tackle the percieved limitations of manual lay-up and drape in manufacture. The machines would replace manual labour and bring down labour costs; reduce learning curve effects and lead time; improve quality and reliability; increase kg/hr production rate; reduce materials wastage and hence materials costs; reduce the requirement for an expanding pool of skilled labour thus debottlenecking production; and lastly not be so dependent on the drape properties of the reinforcement through the use of narrow (typically ~6mm) tape. In practice the AFP machines have rather fallen short of their initial promise, although they do still have a considerable amount of development potential. For example, while touch labour has reduced, a significant level of higher priced machine programming and maintenance has been experienced. Equally on many lines, while the AFP can manage most of the lay-up some hand lay-up is commonly still required. Materials wastage is certainly reduced, although the additional cost of tape slitting from broad goods UD can sometimes more than offset the savings in the costs of materials wastage. If the narrow tapes that are used in AFPs are laid down following geodesic paths (such as a meridian on a sphere) they will generally conform well to the surface without significant wrinkling. However, for surfaces other than simple single curvatures the requirement to follow a geodesic path is too restrictive and there is a need to steer the tapes, which tends to create gaps, and/or overlaps, between adjacent tapes, which can have structural implications, see fig 5. In addition to the gaps/laps, each tow will have to bend in plane to follow the path dictated by the guide/drive roller. As with any bending, this generates a compressive stress on the inside of the radius and a tensile stress on the outside of the radius. There is then a tendency of the fibres to lift off the tool on the outside of the radius and to wrinkle on the inside of the radius. A complicating factor is that for a solid roller the speed of rotation will not match the speed at which the tape is being laid down, leading to a very complicated set of deformations. To date, these issues are primarily tackled by carrying out experimental steering trials rather than by an attempt to understand the details of the drape propeties of the slit tape. In most cases the limiting minimum radius will be of the order of 1m, although the exact radius is more likely to be set by engineering judgement than by a rigorous assessment of the impacts on cost and structural integrity.

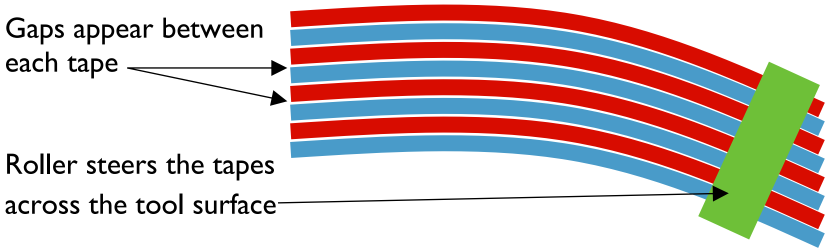


Fig 5. Basics of tow steering in AFP

Fig 6. a. Gantry mounted machine, note the head carries the tape spools in this case and the head itself is very large making it very limited in terms of possible geometry. 6.b. Robot mounted lay-up head. This is much smaller than the gantry mounted machine and the tape spools are held remotely from the head in a temperature and humidity controlled creel cabinet. Image courtesy of the NCC.

There are essentially two major types of AFP. The first uses a gantry to support the lay-up head (fig 6a) which offers great stiffness and stability. The other (fig 6b) uses a robot to carry the lay-up head which results in a more flexible but less reproducible lay-up. The development and increasing use of AFP machines for the lay-up of primary structures in aerospace has been a major driver of work to understand manufacturability with significant academic work in Europe and the USA. Fig 7, shows some structures manufactured using an AFP. This work has helped to develop an understanding of the limitations of AFP [20, 21] especially in terms of geometry and quality/defects. For example the relationship between as-laid consolidation quality and operating conditions for a range of commercial ATL/AFP machines was examined, but no such relationship was found. Looking in more detail it became clear that the actual control over the operating conditions on the commercial machines was rather limited, so an ATL simulator was built that could lay down short lengths of prepreg under very closely controlled conditions. Using the simulator the relationship became very clear; as the lay-up temperature was increased the quality first declined then improved greatly at higher temperatures [22]. The high variability seen in the commercially operated machines was driven by their operating principally in the temperature range where quality was declining. The quality reduction was due to changes in the surface morphology (roughening) of the prepreg as it was heated. It is becoming increasingly clear that our current understanding of the details of the nature and processing of prepreg is still rather incomplete. In recent years more of the very costly commercial AFP machines are becoming available to academic researchers, either in their own labs or through developing relationships with industry and through RTOs such as the UK's National Composites Centre. More capable AFP lay-up heads are also under development to overcome some limitations of current AFP approaches and can, for example, offer a tenfold reduction in defect free minimum steering radius [23].

Fig 7. Winglet skins manufactured by AFP. Images courtesy of the NCC.

Focus has recently returned to how the production of components that cannot be made on an AFP might be automated - which, as noted before, turns out to be most of the small complex parts that abound in aerospace, motorsport and the wider automotive industry. There had been many attempts to use robots to lay up composite reinforcements, using either UD or woven prepreg, but no significant progress had been made and AFP had come to be seen as the default solution, even though its geometrical capability is really very limited. One successful approach is to use robotically laid small patches of prepreg as the small patches are much easier to conform to the tool than large continuous plies. If the UD prepreg is kept very thin the knockdown in mechanical properties can also be minimised. The process shows great promise in many respects, but achieving high rate processing is going to be very problematical.

In order to understand why robotic automation of lay-up has proven to be so difficult it is necessary to carry out a detailed study of how operators actually form and manipulate woven prepreg onto the tool. This study started more than 30 years after it had first been recognized that automation would be needed [24, 25]. It proved to be necessary to develop a structured language which could be used to describe the details of the lay-up process. This turned out to be one of the things needed to be in place to make full use of the VFP software and provide instructions and feedback to the operators. Alongside this the details of the ways in which the component geometry and the characteristics of the woven prepreg impacted on the time taken to complete the lay-up were studied in more depth. Relatively small changes in geometry can be shown to make a very significant difference to the lay-up time and choosing the right prepreg from a manufacturing perspective could halve the lay-up time and hence the direct labour cost. For the first time the ability to define what manufacturable looks like and identify the cost of less manufacturable designs (or material choices) is becoming a possibility, through an improved integration of manufacturing understanding and costing methodologies.

One other issue should be aired briefly here. The academic literature (and most of the more commercial offerings) tends to equate composites manufacture with composites lay-up, and thus equates automated manufacture with automated lay-up. This is far from being entirely correct, even though the lay-up phase is critically important. Twelve major process steps, and a lot of paperwork in an aerospace environment, can be identified from cleaning the mould tool through to inspection and NDT of the finished product. For a conventional complex part lay-up there is probably only a single automated process – ply cutting. Even if AFP is used for ply collation there are still eight manual processes.

There are some tools available to support manual lay-up processes, the most commonly used being laser ply projection. First introduced by Assembly Guidance in 1988, and now widely available from multiple vendors, these systems project the next ply edge position onto the tool to support the laminator to correctly position the ply [26]. Prior to the introduction of laser ply projection the standard industrial practice was that the position of each ply was defined by manually scribing a set of location features for each layer through a template, or stencil. For simple parts, the template was made of mylar. For complex parts, the templates were made of fiberglass in order to conform to the shape of the tool. Using templates to define the location of each ply in a laminate required an inordinate amount of process time, which could be much greater than the amount of time required to actually place the prepreg on the tool. Templates for parts made up of hundreds of plies had thousands of marking points, which made the scribing process extremely confusing. The use of laser projectors to provide the templates greatly improved the efficiency of layup while reducing the scope for error and enabling an increase in the size and complexity of composite laminates.

Although the laser projectors were developed to support manual lay-up processes they have also been developed in support of automated manufacture. For example laser projectors can be used with AFP/ATL where the projected patterns enable inspectors to verify that the layers of material are in the correct locations. See fig 8. In addition, machine vision systems can also be integrated with laser projectors to automate the inspection of laminates, both in the case of hand layup and automated layup. This automated imaging enables the verification of ply boundaries as well as identifying FOD, see fig 9, and measuring fiber orientation and shear as the part is laid up, see fig 10. This automatic inspection and documentation can be used to provide detailed records of as-built characteristics which will be of benefit in forming tighter linkages between design, manufacture and performance.

Fig 8. Green laser lines projected on to the part show the acceptable positional limits for the tapes being laid down in an AFP. Machine vision systems are used es falling outside of specification and can t by the red laser. Image courtesy of Assembly Guidance.

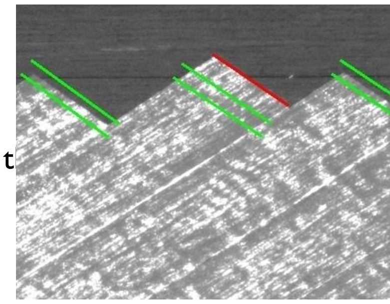


Fig 9. This piece of backing paper was ge and illuminated by laser to enable it to to the next ply being put in place.
Image courtesy of Assembly Guidance.

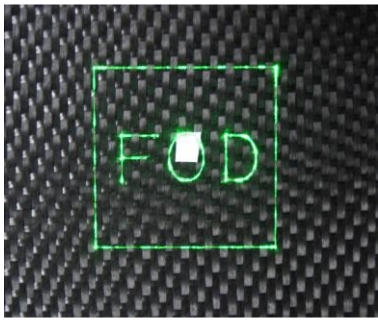
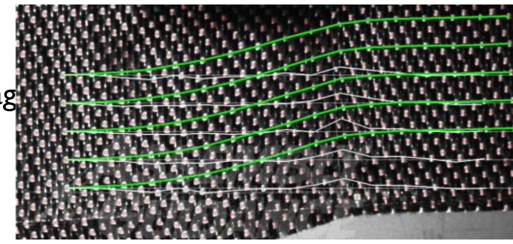


Fig 10. The fibre directions lly identified and traced from the nd weft captured in this imag of Assembly Guidance.



Another reason for trying to understand manual lay-up better is that the expected growth in the composites industry will require the training of a new generation of both designers and laminators. Better training tools are needed alongside everything else, as well as better control in the workplace. A few approaches to developing tools in this area have been demonstrated. Firstly, a low cost alternative to laser projection systems that projects a step by step lay up sequence onto the tool and uses a Kinect games controller/motion sensing device to both control the sequencing and capture lay-up information on the fly [27]. Secondly it has been shown to be possible to incorporate gaming systems and virtual reality approaches initial training routines [28]. Working with the laminators to identify how they approach their work, study has been made of the simple tools they use to make their jobs easier. Most, if not all, laminators have a pocket full of these "dibbers", generally home made from hard plastic, but essentially uncontrolled. It is very hard to think of any other area of the manufacture of aircraft flight-standard components where uncontrolled tools are the norm. Based on a range of the home made dibbers and in-depth discussions with operators a standardised multi-purpose dibber has been developed [29]. This can then be incorporated into training regimes to help to control the variability in the manual lay-up process.

As noted earlier this work stream started with an eye to automating the lay-up process, but identified a number of ways to improve, control and speed up the process by designing in the right features, choosing the right prepreg, supporting the laminators properly and standardising their tools. Taken together a real reduction in cost and improvement in quality is available, potentially making the development of cost-effective automation even more difficult, by reducing the effective costs of manual lay-up. A very recent development has been the robotic lay-up of a relatively complex honeycomb cored sandwich panel from woven carbon fibre prepreg with a quality indistinguishable from that made by a skilled laminator [30], figs 11 & 12. To the author's knowledge this is the first such demonstration, and it perhaps seems ironic that it has been enabled more by studying what laminators actually do than by any advances in robotics, but the reality is that without that knowledge the task would have been infeasible.

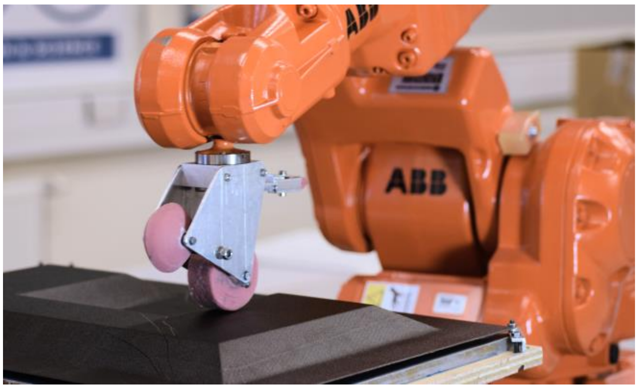


Fig 11. Robot fitted with a selectable set of end effectors forming a complex sandwich panel.

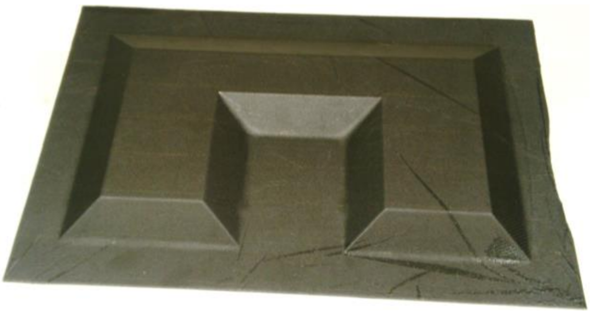


Fig 12. Complex sandwich panel moulding as shown being laid up in fig 10.

The trajectory for this development is illustrated in fig 13. The starting point was the use of VFP software to simulate the lay-up appropriately. This was followed by the development of low cost operator support tools, step by step manufacturing instructions, and appropriate hand tools. The detailed understanding coming from that work enabled the development of the automated solution.

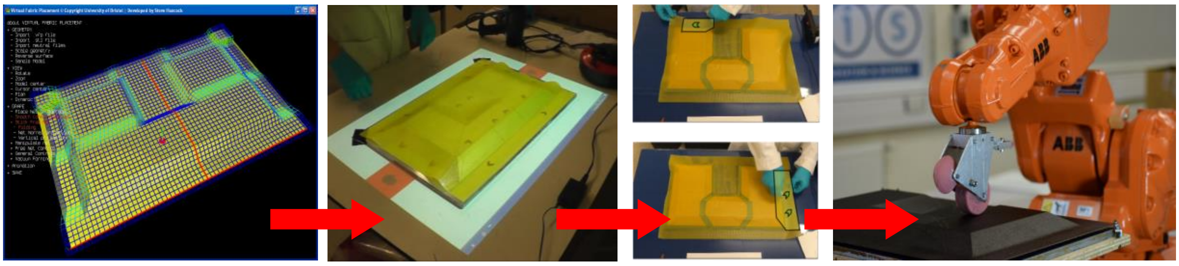


Fig 13. Development trajectory required prior to robotic automation of complex lay-up

Automating woven reinforcement lay-up can be thought of as the complex manipulation of a simple material. The opposite case might then be thought of as the simple manipulation, e.g. press forming, of complex reinforcements - which essentially means how can a reinforcement be made that behaves more like a metal so that it can be embossed or stamped with a clamped edge? A recent development in this area is a novel fibre alignment process by which short fibres, including recycled fibre, can be aligned to a very high degree to give a truly formable material [31]. Material made this way has just taken the record for the strongest material made to date from aligned short fibres. It is very early days for this development and it may not be possible to commercialise the process, but it does very clearly indicate that there may still be life in concepts that were first being explored more than 40 years ago.

2. Resin Transfer Moulding

Towards the end of the 1970s several groups were looking at the need to meet requirements for very complex geometries with tight geometrical tolerances, which really could not easily be manufactured in typical, single sided autoclave tooling. The RTM process had essentially been invented and patented in the 1950s (32) only to be very largely forgotten (at least in the carbon fibre composites arena), needing to be reinvented, and oddly enough repatented, later. Various product development exercises in a number of companies had very clearly identified the advantages of RTM in terms of process robustness, dimensional reproducibility and geometrical complexity in general industrial applications using glass fibre reinforcements. To transition the technology for aerospace, meant demonstrating that carbon fibre/epoxy structures could be reliably manufactured, incorporating features difficult or impossible to achieve in an autoclave. The necessary technology was developed and rapidly matured through a series of small demonstrator contracts (fig 14), and a contract was won to develop aircraft flight components. These were of very complex geometry; they were assembled into a mould tool from a number of individual preforms, most of which were stamped from woven cloth in simple matched preform tooling, although UD elements were also used (fig 15). The preforms generally consisted of two plies of woven cloth, each coated with a small amount of a thermoplastic powder binder which could be heat softened prior to forming. Once formed and cooled the binder held the layers of formed cloth together to give a robust, stable and handleable preform. This mechanical preforming of reinforcements to be assembled into a mould tool, represents the link between the two major elements of the author's work, drape and RTM. The mould tool was then closed and resin was injected under pressure. The actual RTM was carried out in rigid metallic tooling. Prototypes were very extensively tested and approved for use on aircraft. A production line was built for the volume manufacture and parts went into commercial service.

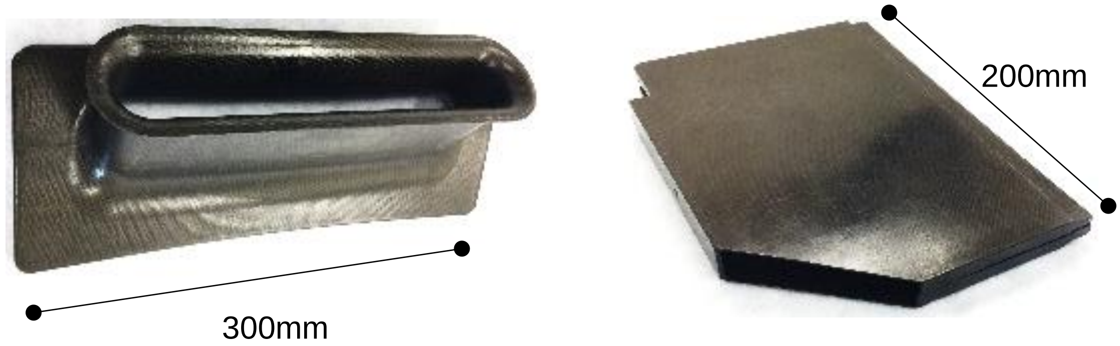


Fig 14. Early aerospace RTM prototypes. Left: a complex engine pylon deicing duct with a major undercut feature, made using a bismaleimide matrix for >200degC service. Right: an electronics cassette with essentially zero radii of curvature corners. Neither part could be made at that time using conventional autoclave moulding techniques.

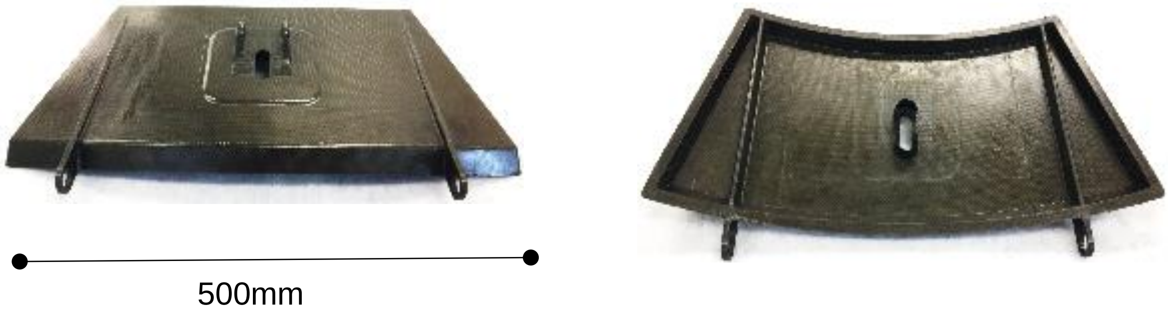


Fig 15. Left: front and rear views of the main moulding of an early (1989) RTM production component (the full assembly consisted of this moulding and a second RTM moulding bonded around a honeycomb core).

There are probably three points that can be made about this project. Firstly, more than 25 years later the author is not aware of any significantly more geometrically complex parts being made today. Secondly, no flow, cure analysis or other process simulation tools were used in the development - as none were available. The same is true of drape models for the stamped parts, where some preforms were made in double-acting tools - way beyond the state of the modelling art in the 1980s. It's not certain that any of today's computer based resin flow models would really cope with the complex geometry and internal resin gating that were used within the mould. The simple approach was taken that if the tools were tightly sealed, all the air was evacuated from a completely dry preform, and a resin was used that had a long open time before significant curing at the injection temperature, then the details of resin flow would look after themselves, and this proved to be the case. Lastly, once the line had been debugged, the production proved to be very reliable with a much lower shop reject rate than the lines in the same factory making much simpler honeycomb cored sandwich panels by an approach based on manual lay-up of woven prepreg and autoclave moulding. Most of that reduction could be put down directly to the thickness control made possible by rigid tool RTM.

Too many of the papers describing the process simulation of RTM start with some variant of the statement that "Without computer simulation components cannot reliably be made by RTM" – it can clearly be stated without any hesitation that they can. Acting rigorously on a knowledge of the fundamental quality drivers can deliver reliable production in many cases, although process modelling can certainly help it is not always critical; understanding the fundamental quality drivers is however always critical. Recent work taking into account stochastic effects to handle in-process variability does, however, offer real promise (34). It can also be noted that BMW's i3 body shell mouldings are made in essentially the same way as the parts described here, from a number of relatively simple pressed preforms assembled in the tool and infused with resin to deliver a complex moulding. Other approaches to the manufacture of preforms have been developed over the years including the use of a variety of stitching techniques, for example to attach stiffening stringers to skins. These methods can be aimed at simply providing a handleable preform [34, 35] or at developing an element of 3D reinforcement using stitching or tufting with a structural thread [36].

Rigid tool RTM has become a very capable process that can be applied to a wide range of part geometries and scales. Fig 16 shows the range of part sizes that are routinely dealt with. The largest part in fig 16 is the glass fibre reinforced cored sandwich panel spinner of 1.2m diameter, at the other end of the scale parts weighing only a few grams have successfully been made by RTM.

Fig 16. RTM can be used to manufacture parts of a very wide range of geometries, materials and scales

Alongside rigid tool RTM a number of other variants of resin infusion processes have been developed based on single sided tooling and vacuum providing the pressure to drive the resin impregnation (37). These processes are used, for example, in the manufacture of boat hulls and wind turbine blades, Siemen’s achievement of a one-shot resin infused blade requiring no assembly being a notable achievement. Fig 17 shows a resin infused tufted foam cored sandwich panel which has been subjected to a very severe edgewise impact, (typical levels for automotive utility pole impact)

Fig 17. Resin Infused sandwich panel after heavy edgewise impact.

Whilst very severe damage has been done to the panel in the immediate vicinity of the impactor, associated with a very high level of energy absorption) no significant damage has been experienced remote from the impactor. By contrast an equivalent panel without the through thickness reinforcement would be completely destroyed.

The current emphases in the area of Resin Infusion processes are on the use of single sided approaches for ever larger structures and on High Pressure RTM for high volume automotive structures. The HPRTM processes are capable of cure cycles in the range of minutes, using injection pressures up to 100 bar in very heavy, and very expensive, presses, see fig 18.

Fig 18. Typical large scale HPRTM press. Image courtesy of the NCC.

The critical differences between conventional RTM as it has been used in advanced applications with carbon fibre and HPRTM lies in the injection pressure and the speed of cure of the resin. In conventional RTM the resin injection and cure processes are essentially sequential, which makes it relatively straightforward to model both processes. Equally, the speed of resin flow is relatively low so that there is little interaction between the reinforcement and the flowing resin, so that for most purposes the reinforcement geometry can be assumed to be fixed throughout the injection. For HPRTM neither assumption is valid, greatly increasing the complexity of modelling [38]. In spite of the difficulties in modelling it will be more important to build a strong modelling capability for high volume manufacture by HPRTM than it has been for low volume conventional RTM, if we are to achieve reliable mass production. Automotive structural components manufactured by HPRTM are likely to be the first truly mass production carbon fibre reinforced structures (>100,000s parts/year of a single part type. Composite structures on aircraft such as the Boeing 737 or Airbus A320 families may require in excess of 100,000 carbon fibre parts a year today but only require hundreds of each specific part).

3. Defects and Variability in Composites Manufacturing.

3.1. Introduction.

The author first became interested in defects and variability in composites manufacturing as a result of working as part of a product improvement team tasked with improving quality and right first time yield on a line manufacturing large numbers of aircraft wing sandwich panels. The morning was spent examining defective panels in some detail, and the afternoon tracking them around the shop floor trying to determine where the defects arose. Things started to improve when a well-structured quality and defect database was instituted which allowed the real problems to be identified, and the defect count to be pushed down. One outcome of spending very many days and weeks linking the activities of the Materials Review Board and the shop floor was the recognition that very many, if not most, of the defects had in essence been designed in. To a large extent the need to dig deeper and deeper into defects and variability and how an understanding of Design for Manufacture might be achieved has been a major feature of composites manufacturing research in recent years. This is really the nexus at which composites manufacture and structural integrity meet as the performance of the laminates and components are essentially controlled by details of the micro and mesostructures, and the residual stresses that are generated in manufacture as a result of design and manufacturing decisions.

An approach to defects has been developed based on taxonomies of both defects and sources of variability [39]. The defects that have attracted most attention have been those relating to fibre waviness, both in and out of plane. These have been studied in a wide variety of ways, from characterising and testing incoming materials and samples cut from production parts, to devising manufacturing relevant and reproducible ways of generating some of the defects seen on production parts, to generating highly controlled defects with very well defined, if slightly unrealistic, internal geometries. Both RTM and bag moulded parts have been considered and the many processes leading to wrinkle formation have been studied [e.g. 40, 41, 42, 43]. So it can be said with complete clarity that wrinkles are a bad thing; that they cause a very significant reduction in performance in static and fatigue strength, at least when coupons are being tested where the defects are of the same sort of scale as the width of the sample. It might reasonably be objected that that was known before the research was started, and that the more important question is really how big the defect has to be, in relation to the structure's size before it becomes a structural concern. This is actually not a question that can realistically be asked in an aerospace context, as the fundamental design assumption would be that the strength of the whole structure should be written down to that of the weakest link. If that assumption was really being taken entirely seriously the industry would probably be even more concerned about wrinkles than it currently is.

3.2. In-process inspection and defect identification

One focus of current research is to identify the emergence of defects during the manufacturing process. As plies are added to the tool, whatever the process used there are opportunities for defects to be incorporated. For example fig 19 shows fibre buckling in an AFP lay-up that would be seen as fibre waviness in that ply after cure.

The two main defects that should be avoided are fibre waviness and fibre bridging. Both of these defects can significantly reduce the component's structural strength, as well as generating dimensional errors and contributing to dimensional variability. In traditional manual lay-up the laminators can, in principle, provide a ply by ply inspection of the lay-up quality to avoid the inclusion of these defects, although in practice poor training or a push to maximise output can easily undermine the effectiveness of this laminator inspection. With the move to automated production by whatever means comes a requirement for automated inspection.

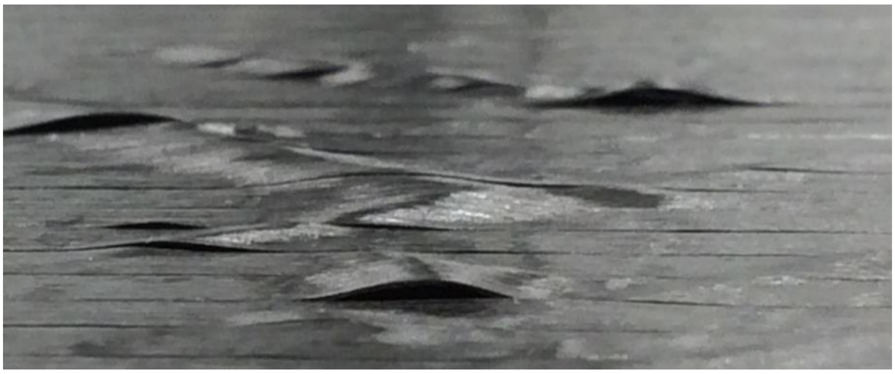


Fig 19. Incipient fibre waviness defects in an AFP lay-up. If additional plies were laid down over these buckled tows an internal fibre waviness defect would be formed.

Whatever the inspection process chosen there is a need for fast and reliable inspection with a minimum of false positives and false negatives. Techniques such as 3D laser surface scanning have been tried. The advantage of this sort of technique is that in principle it gives an absolute measure of whether the ply is in the right place after lay-up or consolidation. However the technique is relatively costly and the speed of scanning and data analysis is currently too slow as the last ply laid must be fully inspected, and if necessary corrected, before the next ply is added. The use of an approach based on the projection of a set of laser spots in a highly controlled reference pattern together with image capture and analysis offers a potentially very valuable solution, for highlighting inconsistencies in the lay-up. This does not give an absolute measure of the ply position but is capable of giving a very immediate and actionable relative impression of the quality metrics. Figs 20 and 21, show wrinkles in an AFP lay-up and a draped woven cloth, and a bridged region in a sandwich panel ramp respectively.

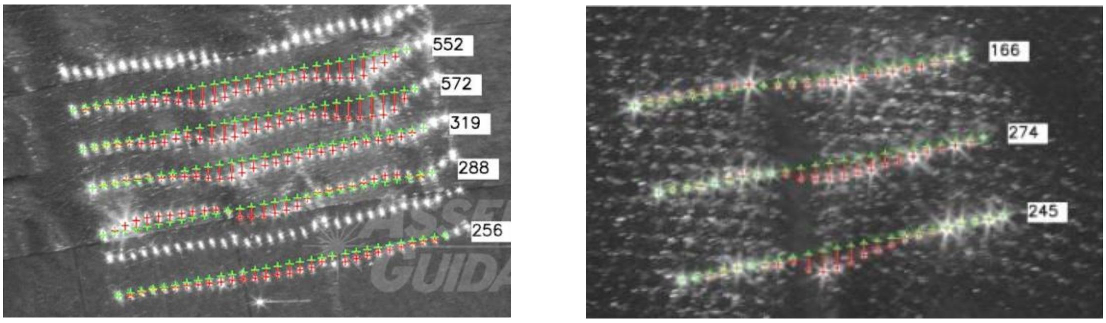


Fig 20. Left, wrinkles in an AFP lay-up. Right, wrinkles in a draped woven prepreg cloth. Both clearly visualized, automatically identified and measured using a regular array of laser dots. Image courtesy of Assembly Guidance.

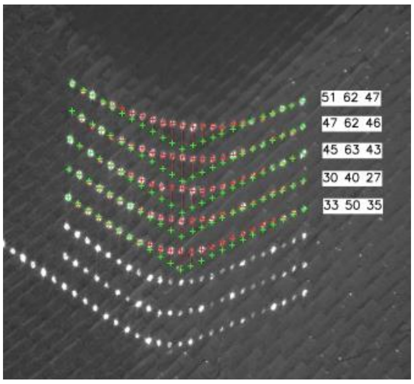


Fig 21. Bridging in a woven cloth prepreg lay-up clearly visualized, automatically identified and measured using a regular array of laser dots. Image courtesy of Assembly Guidance.

The aim of this sort of real time process monitoring is to allow production to be stopped and problems to be resolved without any delay. This should significantly reduce scrap and rework, along with providing data on optimizing for speed and quality, feeding back into the developing Design for Manufacture database.

3.3. Dimensional fidelity

Dimensional fidelity issues have focussed on two areas, thickness tolerances in autoclave moulding, where much of the focus has been, rightly, on incoming material variability and on spring-in and associated residual stresses and fitting stresses. It has been known for as long as there has been a carbon composites industry that the shape of a hot-cured part will not be the same as that of the tool. A 90° corner tool will generally produce an approximately 89° moulding for a 180° C cure, assuming a balanced and symmetrical laminate. If a part must fit to close tolerances the tool geometry may well have to be modified to get the final geometry correct, or at the very least within the tolerance band. We have quite a good handle on these issues now [e.g. 44, 45].

There are really three elements to the spring in. A simply calculated geometrical effect due to differences between in-plane and out of plane thermal expansion; this accounts for about half the total. An additional through thickness shrinkage due to post-gelation cure shrinkage (pre-gelation shrinkage has no effect), which is often of roughly the same magnitude. These two elements are readily calculable, although measuring cure shrinkage throughout cure isn't trivial; producing a first order estimate based on measurements of resin density and thermal expansion coefficients in the various cure states does, however, give a reasonable result. And lastly, other stuff. This includes interactions between tooling and laminate if they have different CTEs (which is true most of the time, even with Invar tooling if accounted for properly, especially when UD prepreg is used), or direct tension in the prepreg due to reacting the autoclave pressure in a bridged lay-up. These are often taken as second order effects, but can be dominant in some circumstances, see fig22.

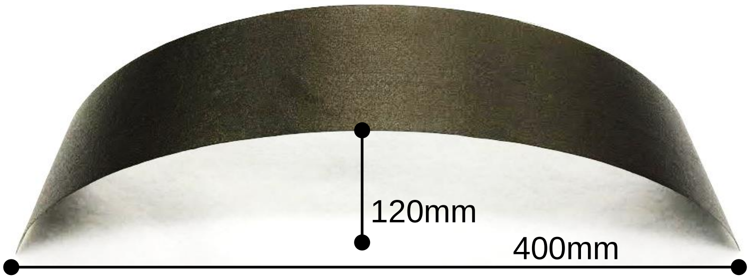


Fig 22. Laminate produced from a flat tool that has been designed to maximise tool/part interactions.

For geometrically complex components, or for components with a complex microstructure that delivers a constraint against through thickness cure shrinkage (e.g. for "noodles" in T sections, 3D woven, Z pinned or tufted structures) the stresses due to resin cure and thermal shrinkage may be sufficient to cause cracking during the manufacturing process – with the potential for very significant impacts on performance and structural integrity and do need to be understood and accommodated in structural analysis and failure predictions, see fig 23.

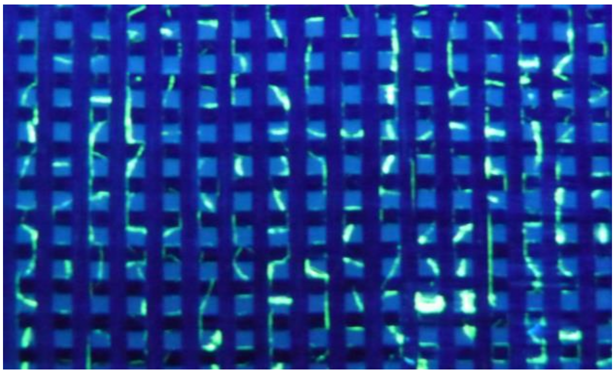


Fig 23. Resin shrinkage cracking of resin rich zones in an orthogonal 3D woven composite. The cracks are highlighted by fluorescent dye penetrant, the blue colour arises from the fact that the matrix resin is also fluorescent.

4. Conclusions, modelling and predictive tools, current status and future work

Latterly effort has been applied to understand the issues around new product introduction and why, despite the solid growth that carbon composites have seen, that growth is not nearly as high as was predicted in the early days of the carbon fibre story [46]. Even with the more automated processes such as AFP, actually getting a factory up and running and operating as predicted is still proving to be problematical [47], and these factory level issues have received very limited academic attention.

As the composites industry has developed a wide range of modelling and predictive tools have become available that, in principle, support all phases of the composites design and development cycle. From a business perspective the most important of these is perhaps costing as if this is wrong the future of the company could be at stake. Costing software is available from several vendors and may be stand alone or integrated into CAD/CAM or similar software design and analysis suites. It is well known that the great bulk of total project costs are fixed by decisions on materials, process and geometry that are made at an early stage of conceptual design. It is an unfortunate truth that at the point in any project when there is the potential to make the biggest impact on total project costs the tools available to quantify that impact are at their weakest.

Parametric costing relies on having a good, reliable and critically assessed database of past experience to work within (extrapolating in parametric costing is very dangerous). For designs that fall within the previous experience these models are fit for purpose. If the target is to design for significantly reduced costs then more or less by definition a costing approach that relies on using the same designs as in the past is not going to be a very effective tool. On the other hand bottom up costing relies on being able to define the process steps with sufficient granularity to attach a cost to each step and is amenable to use with novel designs – but this level of detail is only likely to be developed in detailed design, again limiting its utility in the early stages of design. This impasse is one of the reasons that many designs do copy previous practice, even though the costs cannot be significantly reduced they can be predicted with better fidelity – which is often the critical factor in a commercial environment. It is essential to have costing as a central part of the design process, but it's undeniably difficult to do it well.

Many of the CAD/CAM tools essentially focus on automating the work flow in composites design for large or complex structures, where there may be thousands of individual plies that must be drawn and multiple design constraints that must be satisfied in a typical aerospace environment. The use of a wholly manual design process would be uneconomically time consuming in this case and the CAD/CAM tools, such as Catia or Fibersim, are extremely successful in achieving a detailed design time reduction, and will, for example, output and link drape predictions, flat ply geometry, nesting, ply cutting, AFP control and laser projection aids. These tools really support the detailed design phase and the transition from that phase into manufacturing. They are rather less effective in supporting the earliest design stages where, as noted before, the cost of the project as a whole can be determined. In an aerospace environment this may not be an issue as much of the design freedom is constrained by certification and similar requirements and cost-efficiently meeting that constraint set is of primary importance. There is a lack of tools that support Design for Manufacture in its broadest sense, (rather than design for the transition into manufacture), largely driven by the rather poorly developed knowledge bases of design features and their manufacturing impacts.

Beyond the integrated tool suites there are specific stand-alone tools that can be used for everything from the design of woven cloths (e.g. TexGen, Wisetex) to flow analysis in RTM (e.g. LIMS, RTM-Worx, PAMRTM) to stamp forming analyses (e.g. PAMFORM, ANIFORM), to cure and distortion models (e.g. Compro, LMAT), as well as a range of FEA tools for stress analysis both static and dynamic.

The common limitation with many of the tools that are available for modelling the composites manufacturing processes is that they are quite effective at, for example, predicting wrinkling in forming ply stacks over an arbitrary geometry by hot drape forming, but have very little to say about how to avoid that wrinkling by changes to materials, geometry or process details. It would, of course, be possible to run the software thousands of times to map out the design space, so long as the software had been validated for that range of materials, geometry and process parameters. The same would be true for simulations of RTM flow accommodating race-tracking due to preform fit to the tool. There are also still gaps in the modelling base. There is for example a lack of validated models that predict the development of contact between tool and prepreg or the development and distribution of tool surface voids or other imperfections.

As noted before the critical point in the development of composite products is the earliest stages of the design process, and this is the area in which the support from modelling and simulation is weakest. In this area the need is probably for ‘good enough’ models that solve with no time delay that allow ‘what if’ studies with little cost or time delay, rather than for very high fidelity models. It may be that the modelling and simulation approach may not be the best way to achieve this and that simple Look-up Tables for best practices for different design types and moulding processes would be preferable. Equally, developing better approaches to design reviews for composites would be of great benefit, even a simple approach based on a design checklist to capture and eliminate common errors could be of great benefit, especially with novice designers.

In conclusion, the analytical, numerical and predictive tools associated with composites design and manufacture have still in many instances not quite caught up with the ability to manufacture the most complex geometries without defects, but they are very much closer today than they were even a decade ago, let alone 50 years ago when the carbon fibre composites story started. The challenge now is going to be how best to disseminate both the tools themselves and the understanding derived from the intelligent application of those tools throughout the industry.

The last decade has seen a very significant increase in the use of carbon fibre composites. Alongside that there has been a growing awareness from the UK and other governments that manufacturing really is important, and money has started to flow in support of that. A major step in this for the UK was the publication in November 2009 of the National Composites Strategy. This led directly to the funding of the National Composites Centre, led by industry and operated autonomously within the University of Bristol's Engineering Faculty, with the first build phase being launched in 2010 and operational in 2011, and the second build phase following on in 2013 and operational in 2015. Similar facilities have been put in place in many other countries including, Japan, the USA, France, Germany and Brazil. A real challenge for the future will be how to develop the skilled people we will need in increasing numbers. The first generation of composites people – the men and women that invented carbon and aramid fibre and made them into industrial reality are well past retirement age – even if some of them are still active. The second generation are getting close to retirement now and there seems to be something of a demographic gap opening up, especially in the area of composites manufacturing, which is presenting the community with some challenges.

Lastly, it must be very clearly recorded that the author stopped working in the lab a decade or more ago (and in recent years has spent far too much time with architects and builders delivering new university labs and the NCC). There is absolutely no way that progress could have been without the support of a large number of academic colleagues, postdoctoral researchers and an even larger number of PhD students who were prepared to take the risk of not following a well-worn path, but rather going places without much of a literature base. The composites community is moving towards a real synthesis of design, manufacture and structural integrity in carbon composites, and it is the current and future generation of researchers that will have to be delivering it.

References.

1. Phillips LN. Forming processes for carbon fibre and resin. Composites Volume 1 Issues 2. 1969. 101-103
2. Wildman D. Forming processes for glass fibre and resin – contact moulding. Composites Vol 1 Issue 1. 1969. 35-40
3. Mountfield J. Forming processes for glass fibre and resin – other methods. Composites Vol 1 Issue 1. 1969. 41-49
4. McMullen P. Fibre/resin composites for aircraft primary structures: a short history, 1936-1984. Composites Volume 15, Issue 3. 1984. 222-230
5. Soutis, C. "Recent advances in building with composites". Plastics, Rubber and Composites: Macromolecular Engineering, 38(9/10), (2009), 359-366.
6. Purslow D, Childs R. Autoclave moulding of carbon fibre-reinforced epoxies. Composites, Volume 17, Issuue 2, April 1986, Pages 127-36.
7. Edwards H. Parratt, NJ. Potter, K.D. Synthesis and Application of Aligned Discontinuous Composites. International Conference on Composite Materials Number 2, Toronto, 978
8. Potter KD. The influence of accurate stretch data for reinforcements on the production of complex structural mouldings: Part 2. Deformation of random mats. Composites. Volume 10, Issue 3, 1979, 168-173
9. Potter KD. The influence of accurate stretch data for reinforcements on the production of complex structural mouldings: Part 1. Deformation of aligned sheets and fabrics. Composites. Volume 10, Issue 3, 1979, 161-167.
10. Potter, K. & Ward, C. Draping processes for composites manufacture. Jul 2015 Advances in Composites Manufacturing and Process Design. JAI-ELSEVIER SCIENCE INC, p. 93-109 17 p.
11. Goldsworthy WB. Geodesic path length compensator for composite-tape placement method. Patent US 3810,805, 14th May 1974.
12. Taylor PW. The development and use of a tape laying machine. Symposium on Fabrication Techniques for Advanced Reinforced Plastics. Salford, April 1980. IPC Science and Technology Press
13. Buckingham RO, Newell GC. Automating the manufacture of composite broadgoods. Composites Part A, Volume 27, Issue 3, 1996. 191-200
14. Mack C, Taylor HM, The fitting of woven cloth to surfaces. Journal of the Textile Institute Transactions. Vol 47, Issue 8, 1956.
15. Robertson R.E, Chu T.-J, Gerard R.J, Kim J.-H, Park M, Kim H.-G, Peterson R.C. Three-dimensional fiber reinforcement shapes obtainable from flat, bidirectional fabrics without wrinkling or cutting. Part 1. A single four-sided pyramid. Composites Part A: Applied Science and Manufacturing, Volume 31, Issue 7, July 2000, Pages 703-715
16. Dong, L., C. Lekakou, and M. G. Bader. "Solid-mechanics finite element simulations of the draping of fabrics: a sensitivity analysis." *Composites Part A: applied science and manufacturing* 31.7 (2000): 639-652.
17. Long, A. C., B. J. Souter, and F. Robitaille. "A fabric mechanics approach to draping of woven and non-crimp reinforcements." *PROCEEDINGS-AMERICAN SOCIETY FOR COMPOSITES*. 2000.

18. Boisse, Philippe, et al. "Composites forming." *Advances in Material Forming*. Springer Paris, 2007. 61-79.
19. Development and application of the virtual fabric placement concept for the production of complex shaped components from woven reinforcement. Potter, K. D. & Hancock, S. Apr 2007 SAMPE Europe International Conference, Paris, France.
20. Chen, Jihua, et al. "Impact of layup rate on the quality of fiber steering/cut-restart in automated fiber placement processes." *Science and Engineering of Composite Materials* 22.2 (2015): 165-173.
21. Lichtinger, Roland, et al. "Simulation and experimental validation of gaps and bridging in the automated fiber placement process." *Science and Engineering of Composite Materials* 22.2 (2015): 131-148.
22. Lukaszewicz DHJA, Potter KD. Earles J. A concept for the in situ consolidation of thermoset matrix prepreg during automated lay-up. Composites Part B. 45 (2013) 538-543
23. Kim, B. C., Weaver, P. M. & Potter, K. Manufacturing characteristics of the continuous tow shearing method for manufacturing of variable angle tow composites. Jan 2014. Composites Part A: Applied Science and Manufacturing. 61, p. 141-151 11 p.
24. Bloom, L.D., Elkington, M., Ward, C., Chatzimichali, A.P., Potter, K.D. On prepreg properties and manufacturability. (2013) 19th International Conference on Composite Materials, pp. 4397-4409. Montreal, July 24th-28th 2013
25. Elkington, M., Bloom, L.D., Ward, C., Chatzimichali, A.P., Potter, K.D. Understanding the lamination process. (2013) 19th International Conference on Composite Materials, *pp. 4385-4396*.
26. Blake, S. Replacing composite hand layup templates with a simple projection system. *34th International SAMPE Symposium and Exhibition*. 1989.
27. Such M.C., Ward C., Hutabarat W., Tiwari A. (2014) Intelligent composite lay-up by the application of discrete technologies. Procedia CIRP 25, 122-131
28. Kularatna S. Ward. C. Low Cost Gamified Training for Composite Layup: A Feasibility Study, AMPCS in press (at 20.4.2016)
29. Jones HV, Chatzimichali AP, Middleton RA, Potter KD, & Ward, C. Exploring the discrete tools used by laminators in composites manufacturing: application of novel concept. Advanced Manufacturing: Polymer and Composites Science. 1, 4, p. 185-198 14 p
30. Elkington M, Ward C, Potter K,. Automated layup of sheet prepregs on complex moulds. SAMPE Long Beach Conference, May 2016.
31. Yu, H., Potter, K. D. & Wisnom, M. R A novel manufacturing method for aligned discontinuous fibre composites (High Performance-Discontinuous Fibre method). Jan 2014. Composites Part A: Applied Science and Manufacturing. 65, p. 175-185 11 p.
32. Potter KD. The early history of the resin transfer moulding process for aerospace applications. 1999. Composites part A. 30, 619-621
33. Mesogitis, T. S., A. A. Skordos, and A. C. Long. "Uncertainty in the manufacturing of fibrous thermosetting composites: A review." *Composites Part A: Applied Science and Manufacturing* 57 (2014): 67-75.
34. Beier, Uwe, et al. "Mechanical performance of carbon fibre-reinforced composites based on stitched preforms." *Composites Part A: Applied science and manufacturing* 38.7 (2007): 1655-1663.
35. Beier, Uwe, et al. "Evaluation of preforms stitched with a low melting-temperature thermoplastic yarn in carbon fibre-reinforced composites."*Composites Part A: Applied Science and Manufacturing* 39.5 (2008): 705-711.
36. Cartié, Denis DR, et al. "3D reinforcement of stiffener-to-skin T-joints by Z-pinning and tufting." *Engineering Fracture Mechanics* 73.16 (2006): 2532-2540.
37. Summerscales, J., and T. J. Searle. "Low-pressure (vacuum infusion) techniques for moulding large composite structures." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications* 219.1 (2005): 45-58.
38. Deléglise, M., et al. "Modeling of high speed RTM injection with highly reactive resin with on-line mixing." *Composites Part A: Applied Science and Manufacturing* 42.10 (2011): 1390-1397.
39. K. Potter, B. Khan, M. Wisnom, T. Bell, J. Stevens. Variability, fibre waviness and misalignment in the determination of the properties of composite materials and structures. Composites Part A: Applied Science and Manufacturing, Volume 39, Issue 9, September 2008, Pages 1343-1354
40. Lightfoot, J. S., Wisnom, M. R. & Potter, K.Defects in woven preforms: Formation mechanisms and the effects of laminate design and layup protocol. Aug 2013 In : Composites, Part A: Applied Science and Manufacturing. 51, p. 99-107 9 p.
41. Wang, J., Potter, K. & Etches, J. A. Experimental investigation and characterisation techniques of compressive fatigue failure of composites with fibre waviness at ply drops. Jun 2013 Composite Structures. 100, p. 398-403 6 p.

42. Lemanski, S. L., Wang, J., Sutcliffe, M. P. F., Potter, K. D. & Wisnom, M. R Modelling failure of composite specimens with defects under compression loading. May 2013 Composites, Part A: Applied Science and Manufacturing. 48, 1, p. 26-36 11 p.
43. Bloom, L. D., Wang, J. & Potter, K. D. Damage progression and defect sensitivity: An experimental study of representative wrinkles in tension. Feb 2013 In : Composites Part B: Engineering. 45, 1, p. 449-458 10 p.
44. Radford, D. W., Rennick, T.S. Separating sources of manufacturing distortion in laminated composites. Journal of Reinforced Plastics and Composites 19.8 (2000): 621-641.
45. Ersoy, N., Garstka, T., Potter, K., Wisnom, M. R., Porter, D. & Stringer, G. Modelling of the spring-in phenomenon in curved parts made of a thermosetting composite. Mar 2010 In : Composites, Part A: Applied Science and Manufacturing. 41, 3, p. 410 - 418 9 p.
46. Anna P Chatzimichali and Kevin D Potter. From composite material technologies to composite products: a cross-sectorial reflection on technology transitions and production capabilities. Translational Materials Research, Vol 2. No 2, June 2015
47. Winter, D J J, Jones, C D C, Ward, C, Gibbons, P. M., McMahon, C. A. & Potter, K. D. The Application of a Lean Philosophy During Manufacturing of Advanced Airframe Structures in a New Product Introduction (NPI) Environment. 2013 Advances in Sustainable and Competitive Manufacturing Systems: 23rd International Conference on Flexible Automation & Intelligent Manufacturing. p. 1503-1513 11 p.